Ground vs. Space Interferometry

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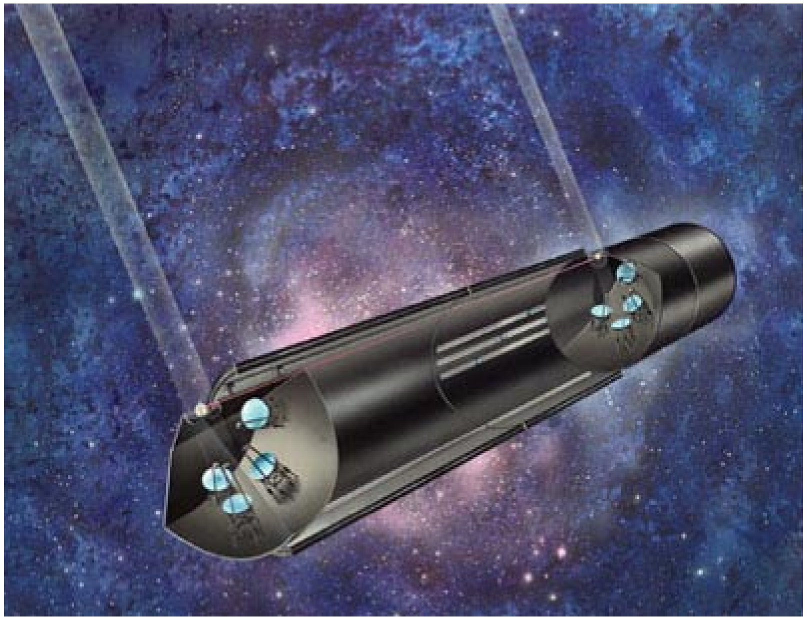
Overview

- Ground and Space Fundamentals
  - Atmosphere
  - Coherence Time
  - Sensitivity
- Astrometry: phase measurement
  - Wide Angle
  - Narrow Angle
- Imaging: visibility and phase measurement
- Planet Detection: visibility and phase control

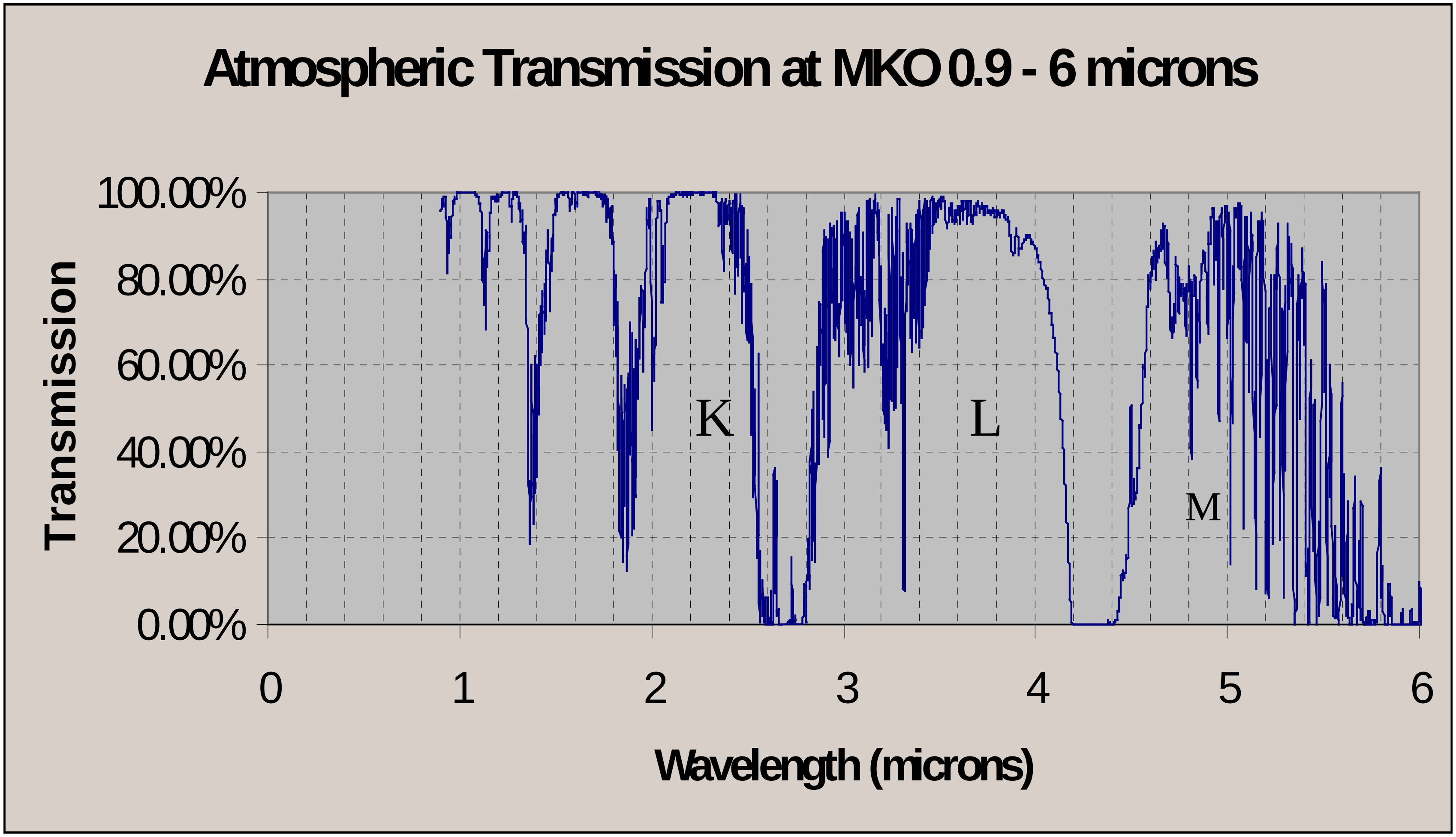
Space Advantages

- Atmospheric transmission:
  - X-ray
  - UV
  - NIR bands between 1-10 microns
  - Sub-millimeter
- Lack of Turbulence
- Easily reconfigurable u-v coverage (spinning the spacecraft)
- Easy to cool optics

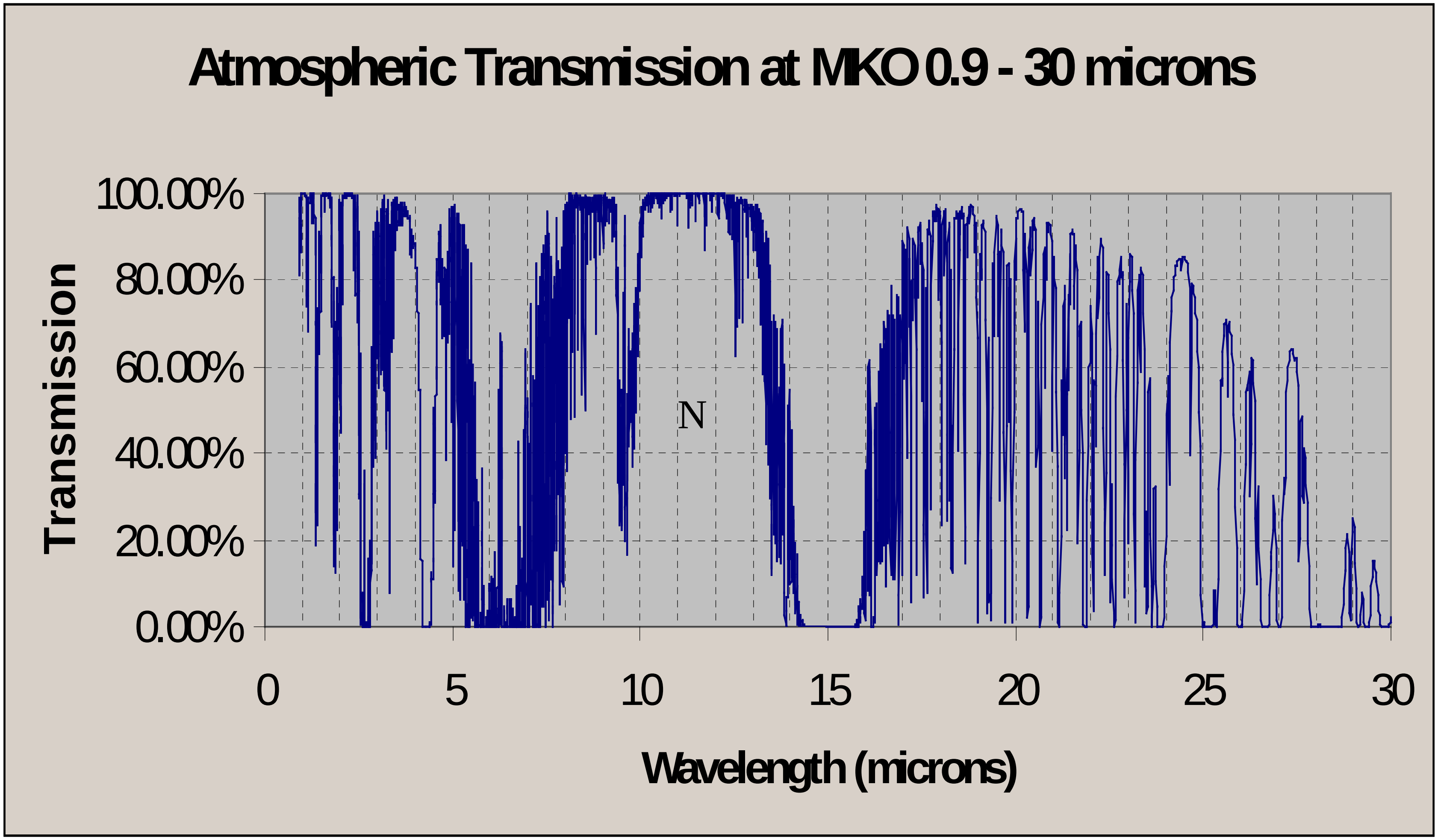


Ground Advantages

- Longer baselines (up to a point)
- Larger apertures
- Upgrades, lifetime
- Cost



These data, produced using the program IRTRANS4, were obtained from the UKIRT worldwide web pages.



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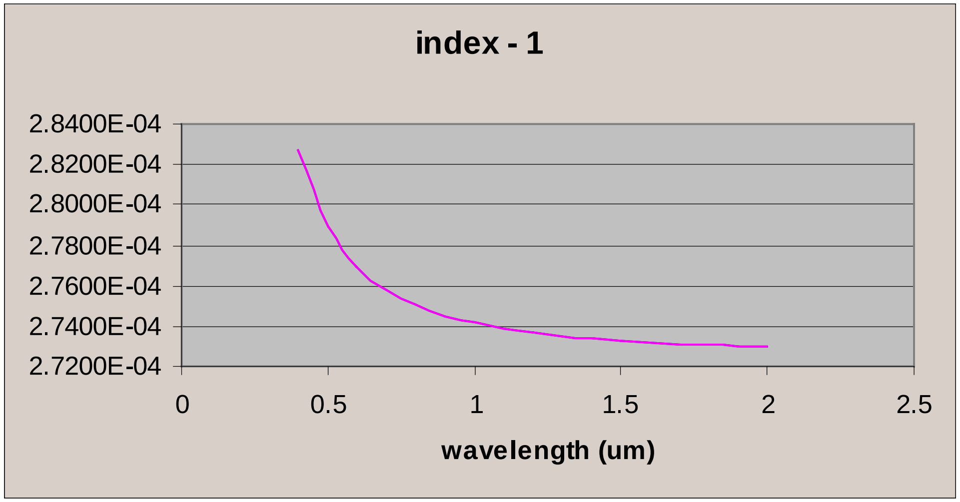
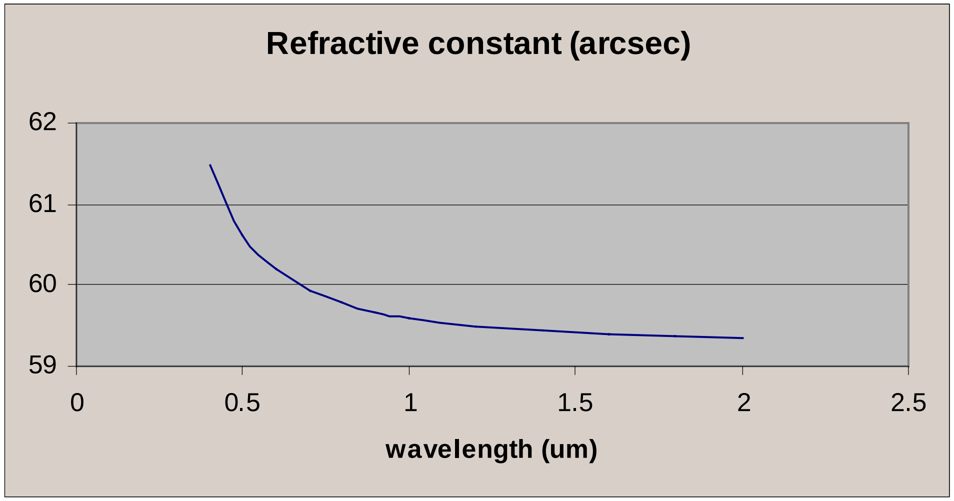
Dispersion

- "Wedges" in atmosphere lead to ~ 20 micron delays in Mark III measurement.
- Measured phase is different in red and blue light by ~ 250 nm over visible spectrum at tan(z)=1.
  - Equivalent to 5 milli-arcsec
- Colavita 2-color technique: remove the atmospheric wedge contribution based on the difference in red and blue phases.
- Improvement of ~ 5 compared to single-color results.
- Limited by water-vapor turbulence





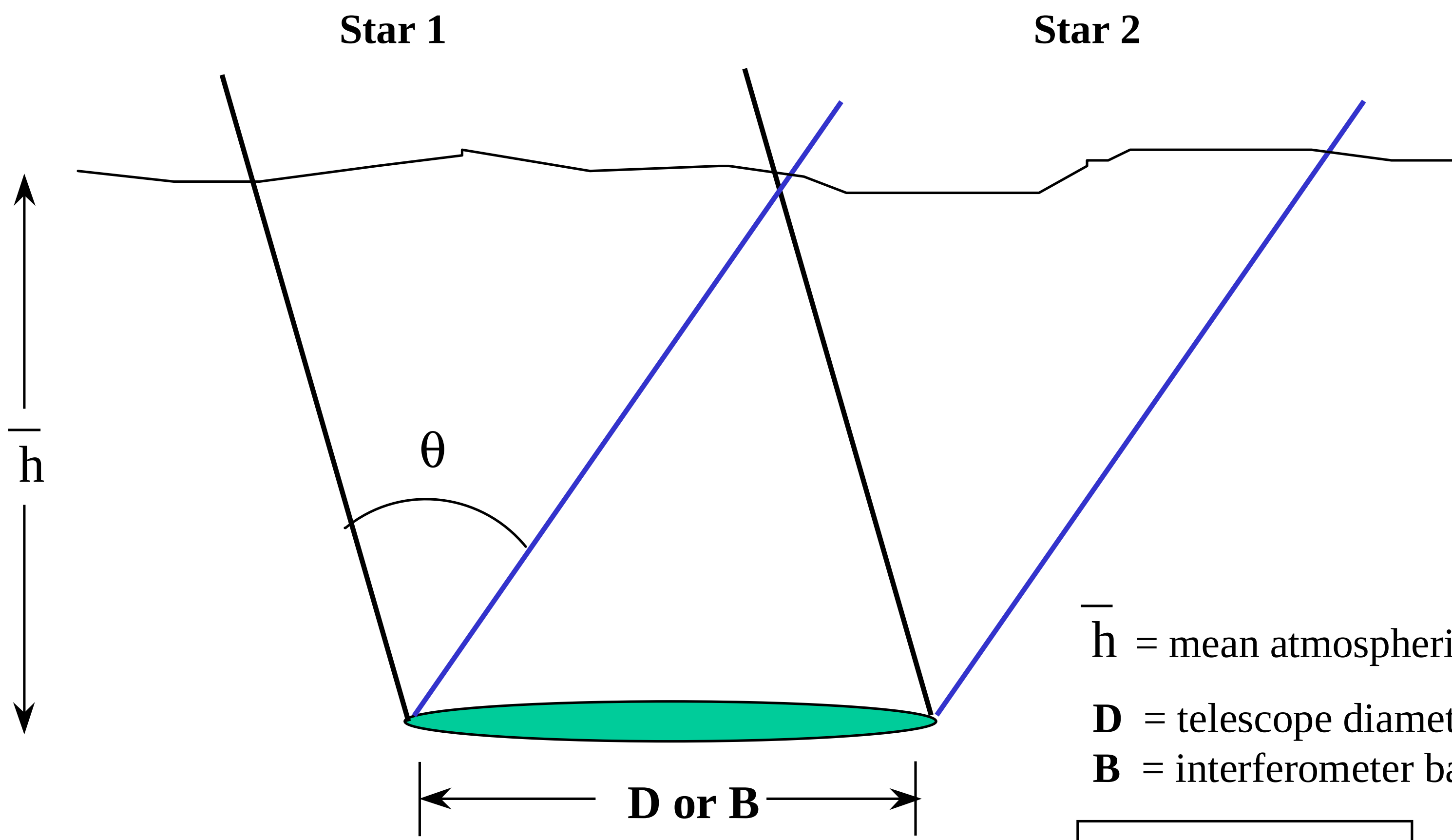
Turbulence

- Wavefronts blow across the instrument
  - Apertures: this is pretty fast, t_0 = 10-20 ms for a 10 cm aperture. Averages as $t_0^{-1/2}$
  - Baseline: large-scale wedges may be huge. The spectrum is not white. Averages as $t^{-1/6}$ (This is a big problem for astrometry.)
- Coherence scale
  - 1 arcsecond seeing, r0 = 10 cm in the visible
  - scales as $\text{lambda}^{6/5}$ (as does t_0)
  - "outer scale" may be hundreds of m
  - Isoplanaticity: region around the target where wavefront r.m.s. difference is < 1 radian
    - This region is a few arcseconds across
    - It limits the useful field for an adaptive optics system.

Above the Atmosphere

- When is one above the atmosphere?
  - Ftaclas et al studied scintillation measurements made from the Mir space station
  - Determined that at 30 km the Fried parameter is 164 m
- A long-baseline interferometer or large telescope will be optics limited at this altitude.
- They show that a Jovian planet could be detected around a nearby star using a moderate telescope on a balloon flight.
- Serviceable instrument, 100 day missions, but as they point out “It’s a long way down!”

Isokinetic Angle



$\bar{h}$ = mean atmospheric height

D = telescope diameter

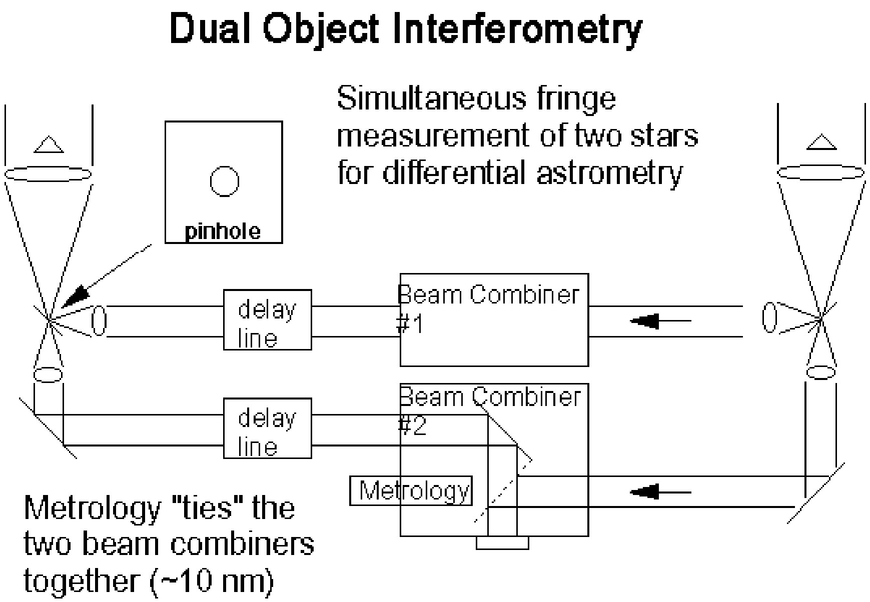
B = interferometer baseline

The isokinetic angle defines the average height where the beams from two different stars no longer overlap.

$$\boxed{\theta = \frac{\mathbf{B}}{\bar{h}}}$$

Narrow Angle (Differential) Astrometry

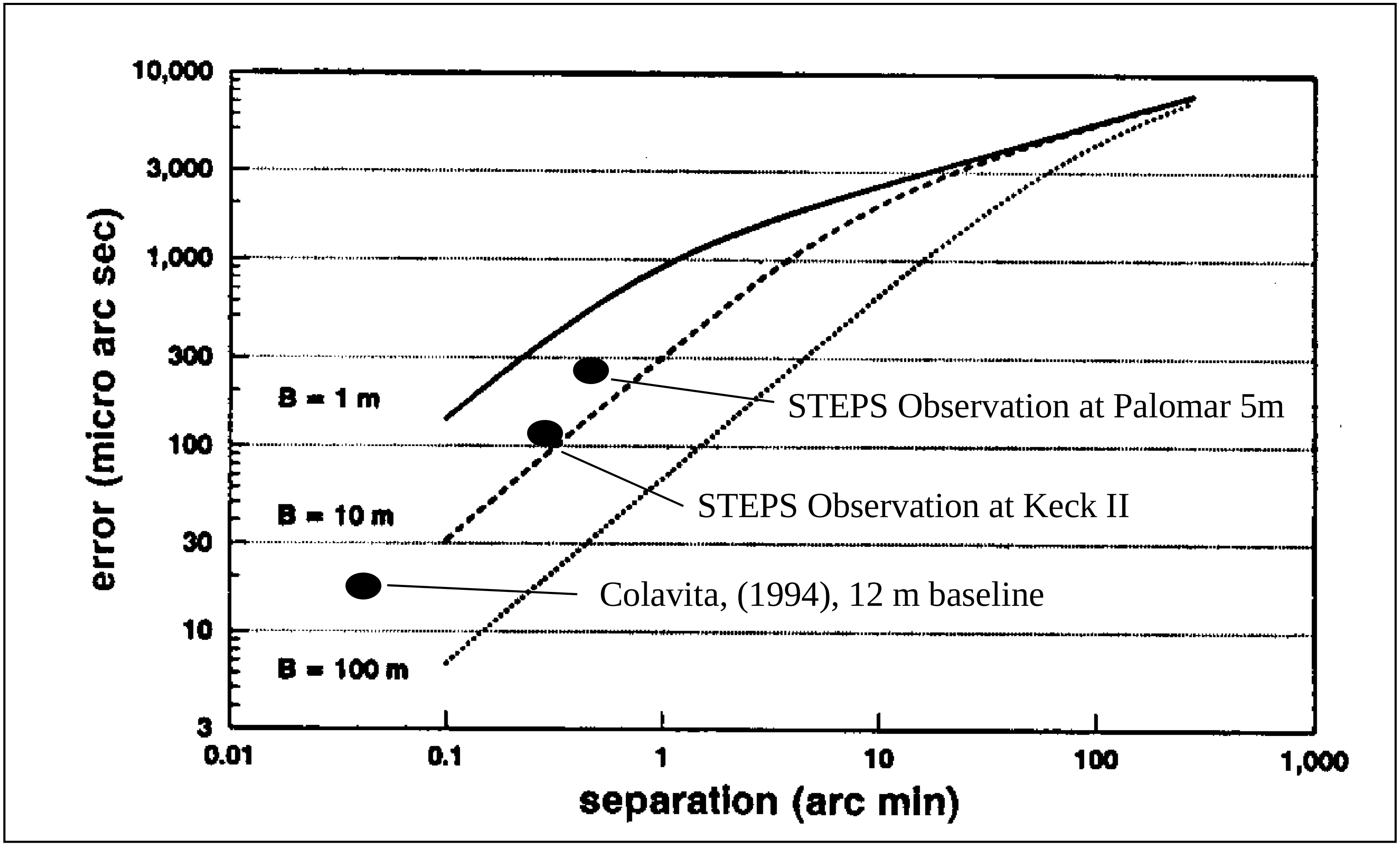
- Very narrow angle
  - Stars separation << isokinetic angle
  - accuracy proportional to star separation and B^(-2/3)
- Not-so-narrow
  - Stars separated by >> isokinetic angle
  - accuracy independent of baseline, proportional to star separation ^ 1/3



Picture downloaded from JPL PTI website

Narrow Angle Astrometric Precision

For a 1-hr long observation in 0.5 arcsec seeing



Shao and Colavita, 1992 A&A 262, 353

Ultimate Narrow Angle Limit on the Ground

- The Keck interferometer may be able to achieve 10 micro-arcsecond relative accuracy between stars.
  - Fractional sky coverage is small, few percent due to sparsity of bright nearby stars
  - This requires 5 nm metrology over 100 m baseline, relative to starlight path.
- The Palomar Testbed Interferometer achieves 10s of microarcseconds to K=13 (assumes bright reference star).
- The best single-aperture astrometry is ~ 200 micro-arcseconds for sources separated by > few arcsec.

Wide Angle Astrometry

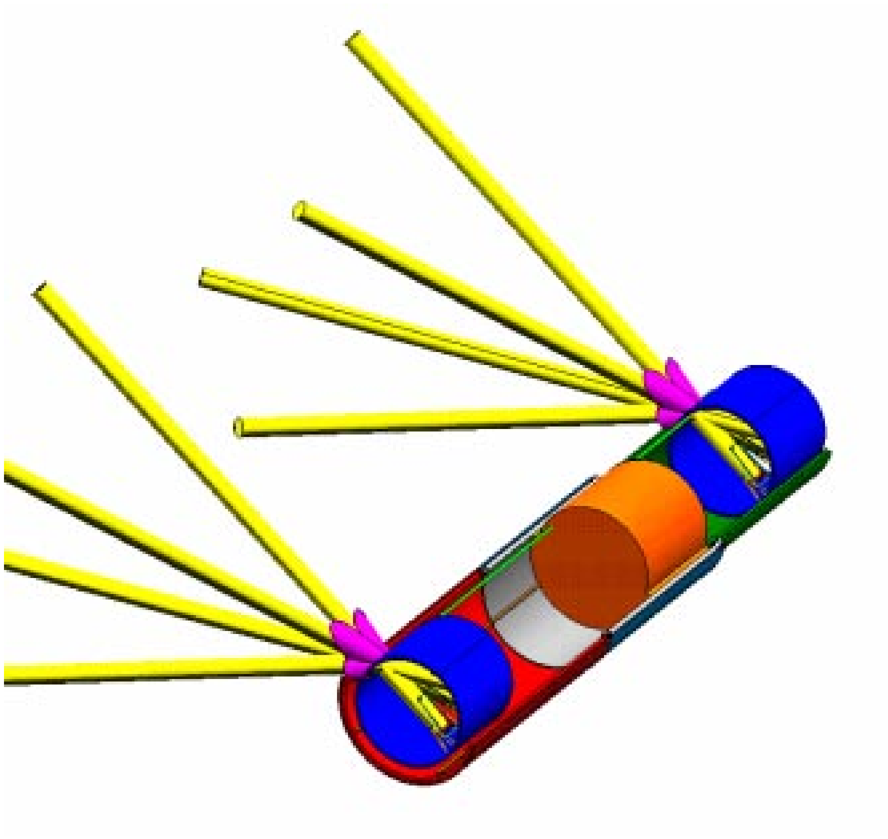
- Ground based: limited by slow drifts in the non-white atmosphere
  - averages as t^-1/6
  - The Mark III did ~ 5 milli-arcsec on stars with V<7
  - NPOI will go fainter but will have similar
- Baseline is stable: few microns/night at the Mark III.
  - Baseline solution is determined by fitting curves to stars using a priori positions.
- In space, the baseline moves
  - "Guide" interferometers are used to measure baseline motion
  - Various schemes link together patches or rings on the sky.

The Interferometer Baseline in Space

- Spacecraft drift because they can
  - Solar pressure, magnetic fields, gravity gradients
- Star trackers measure the angular drift
  - Typically good to better than 1 arcsec
  - Control is typically +/- 1 arcsec
- Hard to do better than this on an interferometer
  - Long thin structures are floppy
  - The end-points thermally deflect by micro-radians with respect to the star-tracker position
  - Joints in deployed structures are weak points.

Baseline phase referencing

- Inertial motion of baseline must be controlled or known to 0.1*lambd/B radians
  - 1 mas for a 10 m baseline in the visible
- That's 10x better than HST
- Requires the development of dedicated star trackers, or
- On-board phase-referencing interferometers
  - Separate (see picture)
  - Internal, a la PTI dual-star feed.



So what if the Baseline drifts?

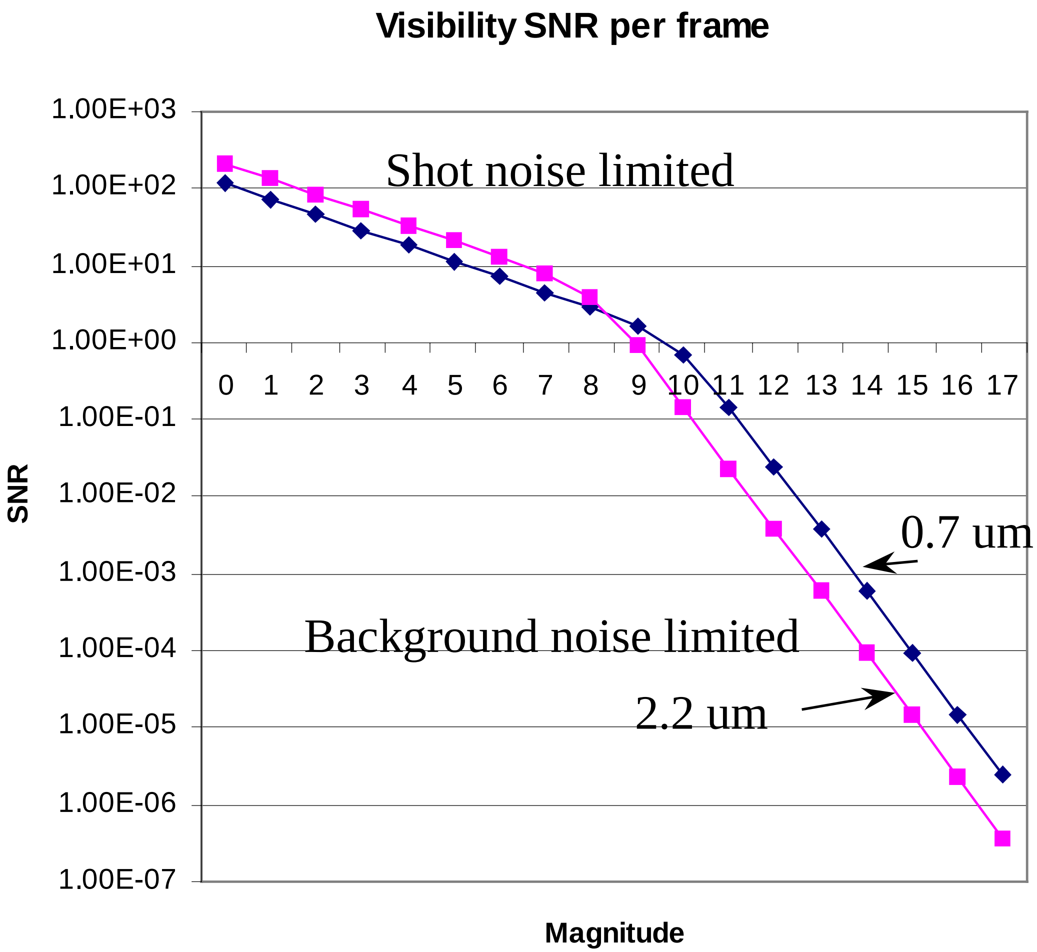
- Resolution is lambda/B = 0.01 arcsec for a 10 m baseline at 0.5 microns.
  - Drift of 1 arcsec smears 100 fringes!
  - This is comparable to the atmosphere
    - But it's measurable and somewhat predictable
    - Delay lines can be moved to compensate the motion
      - This is a new can of worms: dynamical changes in the S/C
- To the extent that the drift is not predictable (say 1% of 100 fringe motion), the spacecraft case is similar to ground-based
  - t_0 = 0.1 sec
  - r_0 is large, similar to adaptive optics case
- *Thus to have an advantage over the ground, a space interferometer MUST have a phase reference.*

Maximum Baseline Length

- NASA is deploying a 60 m boom with an 800 lb mass. (SRTM 3-D Synthetic Aperture Radar)
  - 0.1 Hz boom
  - 100 m is probably the maximum extension of this technology for interferometry
- Separated spacecraft are required for longer baselines

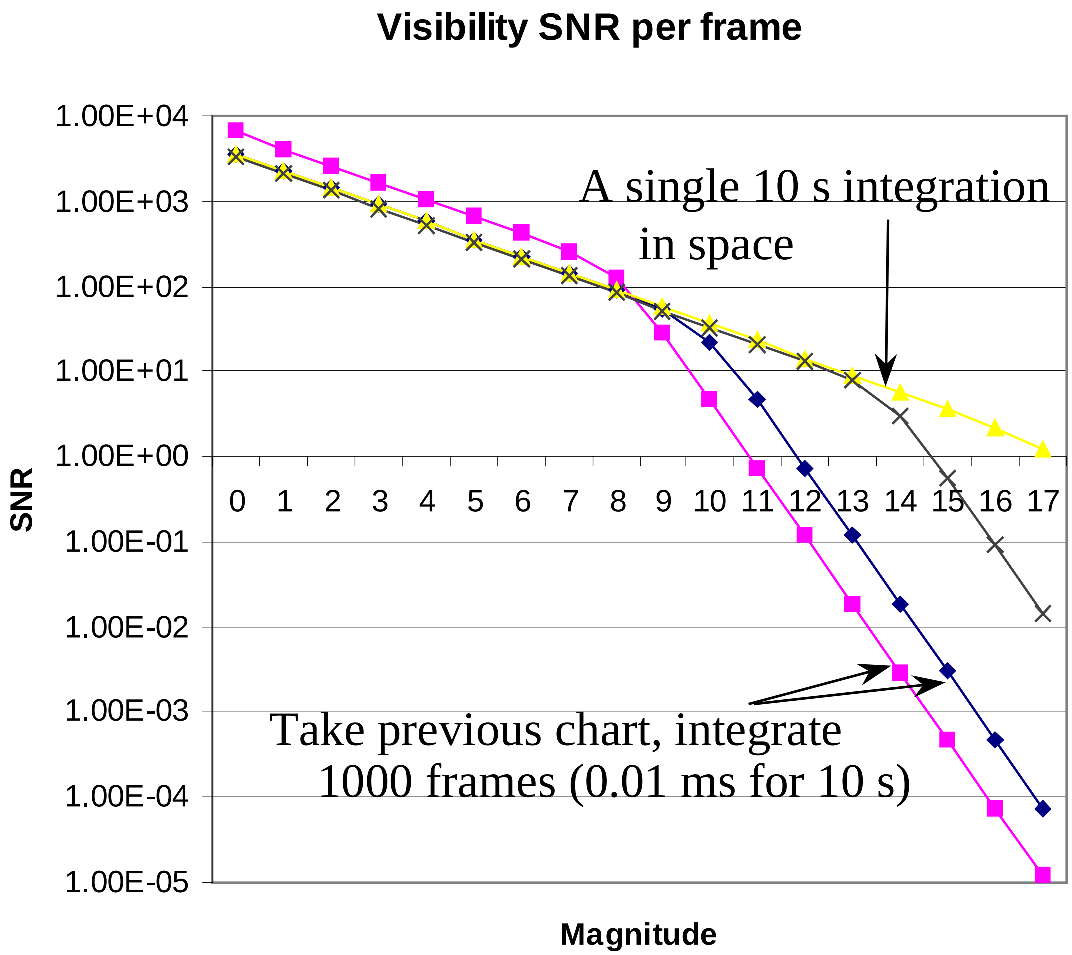
Picture downloaded from JPL SRTM web site.

SNR per frame in a ground-based interferometer



Assumptions:
seeing = 1 arcsec (r0 = 10 cm)
Aperture size = 10 cm (0.7 um)
40 cm (2.4 um)
Throughput = 0.1
Bandwidth = 10%
Visibility = 1.0
Integration time = 10 ms (0.7 um)
40 ms (2.2 um)
0.7 microns: 3 e- read noise/frame
2.2 microns: 25 e- read noise/frame

How does going to space help?

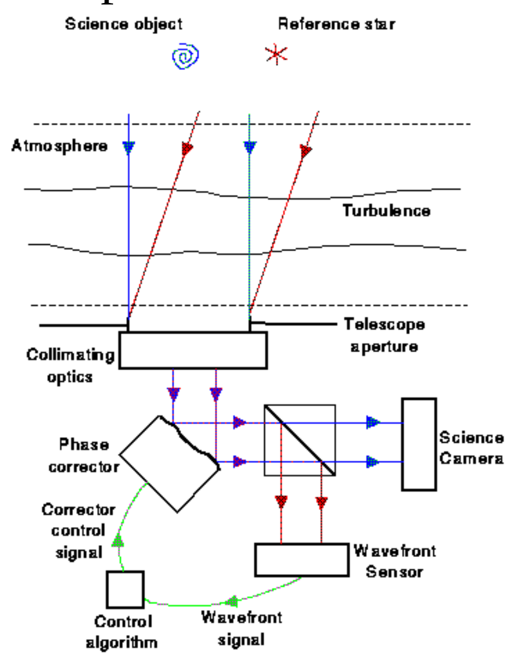


New Curve Assumptions:
seeing = perfect
Aperture size = 10 cm (0.7 um)
40 cm (2.4 um)
Throughput = 0.1
Bandwidth = 10%
Visibility = 1.0
Integration time = 10 s (0.7 um)
40 s (2.2 um)
0.7 microns: 3 e- read noise/frame
2.2 microns: 25 e- read noise/frame

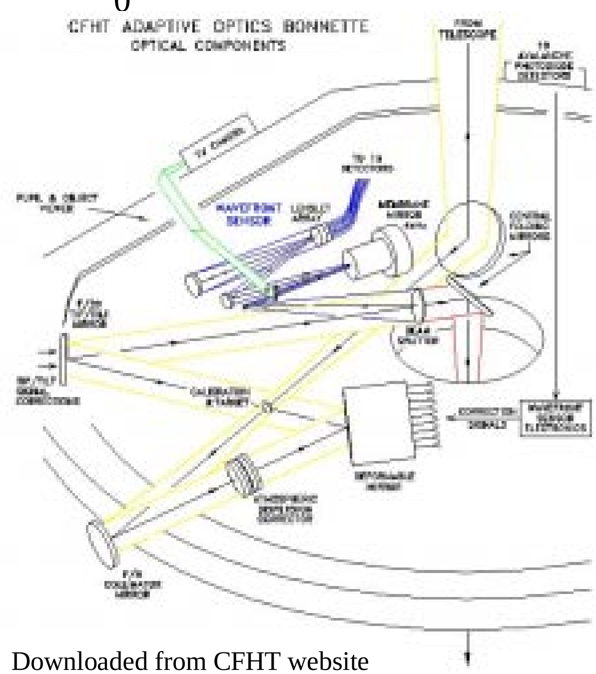
Going to space improves the low SNR region by allowing coherent integration. It does not improve the high SNR region unless aperture size is increased.

Improving the Odds

- r_0 and t_0 scale as $\lambda^{6/5}$
- Photons/coherence volume goes as $r_0^2 t_0$
- Photon limited, SNR scales as sqrt(n)
  - Thus, SNR scales as $\mathrm{sqrt}(r_0^2 t_0) = \lambda^{9/5}$
- When background noise limited, the SNR increases as $\lambda^{18/5}$
- 2.4 vs 0.6 microns, shot limited, increases SNR by 12, greatly increasing number of targets.
- Adaptive Optics can increase the effective r_0

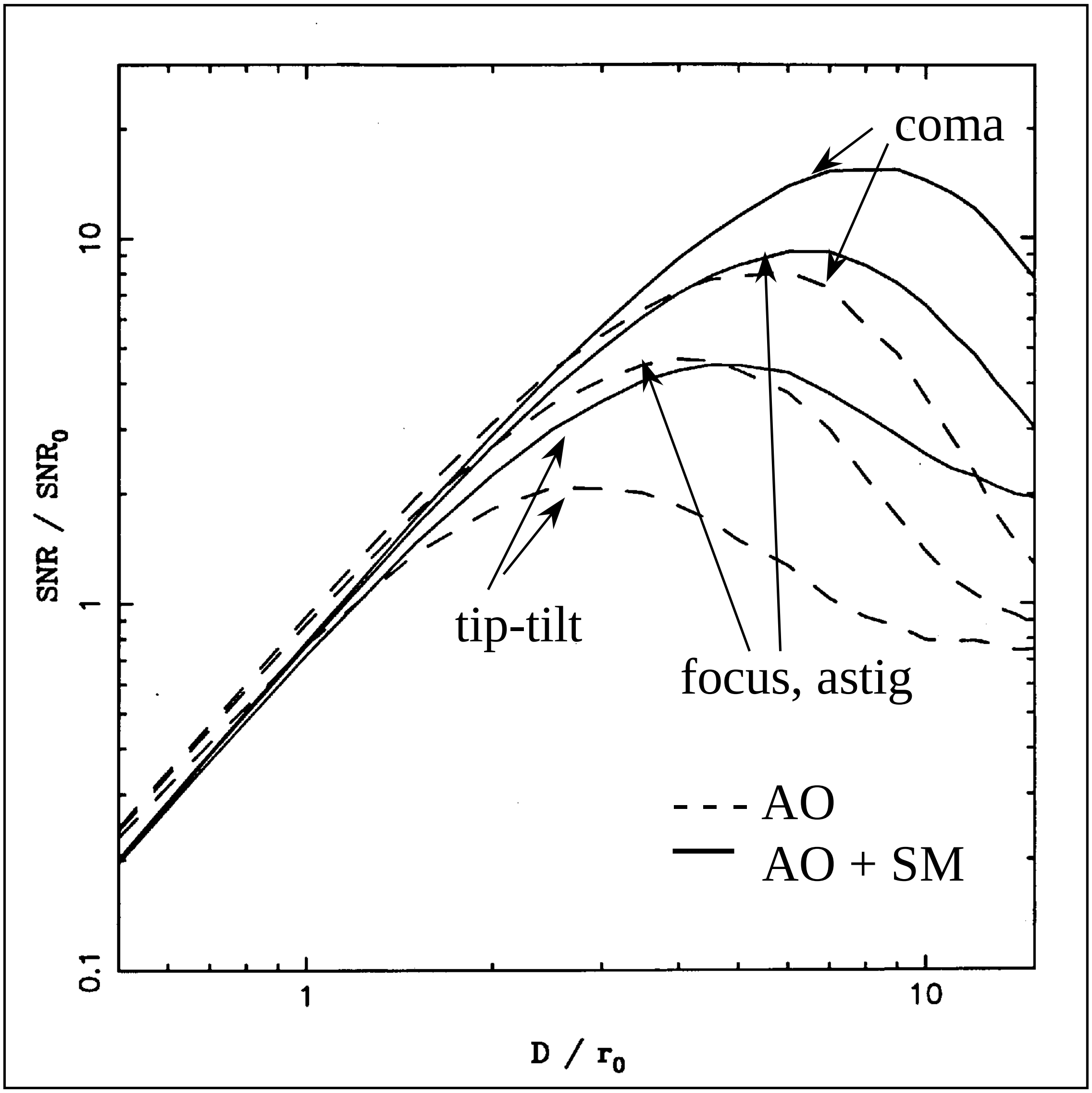


Picture downloaded from
AO Group, Blackett Laboratory,
Imperial College, London



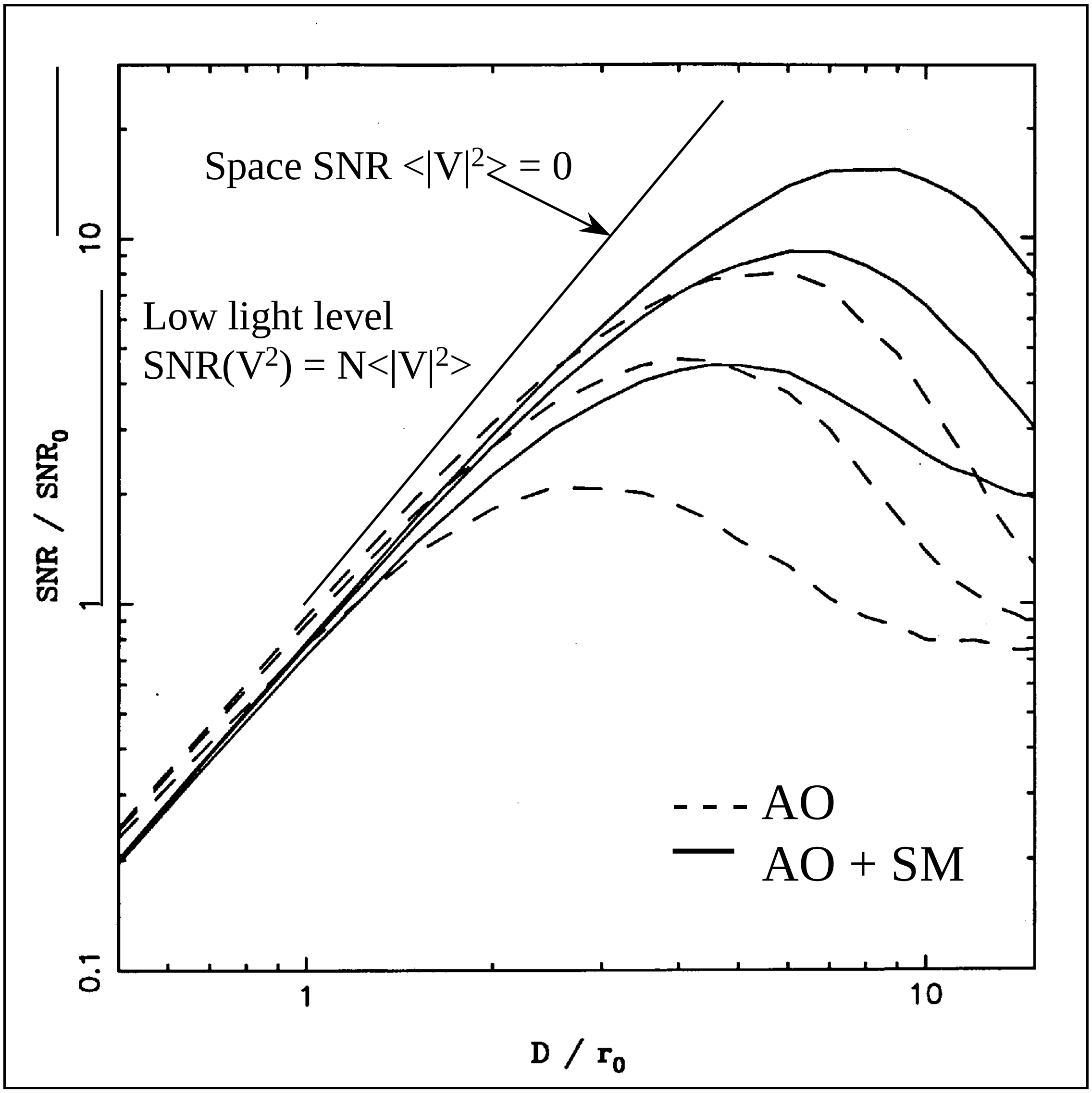
Downloaded from CFHT website

Adaptive Optics and SM Fiber Optics



This plot shows the low-light SNR of V^2 compared to an ideal interferometer having apertures of r_0. The curves show what happens when the first 2, 5, and 9 non-piston Zernike terms are removed. The fiber improves SNR by decreasing sensitivity to visibility fluctuations and filtering out non-coherent light (Buscher and Shaklan, SPIE Kona, 1994).

Adaptive Optics and SM Fiber Optics

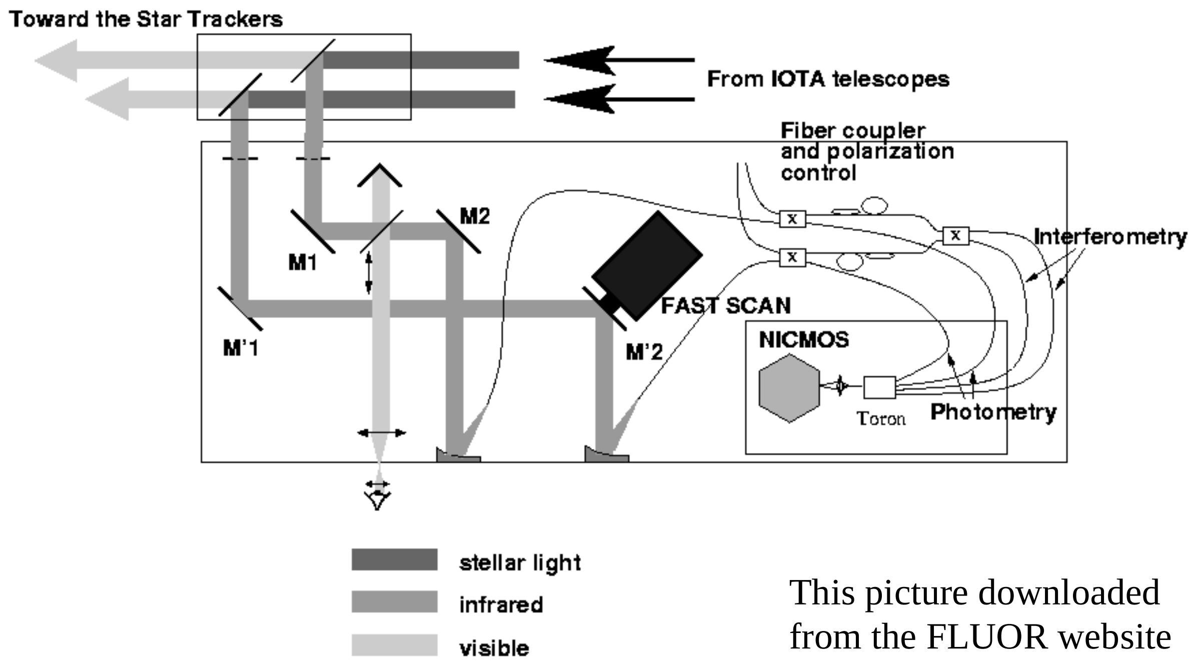


The plot is now annotated to show the efficiency compared to a space-borne interferometer that does not suffer from loss of visibility. At d/r0 = 8, the efficiency of the ground based interferometer is ~ 0.2 in the estimate of V^2.

Ground (+AO + Fiber) vs. Space Efficiency

- At d/r0 = 8, space is 5x more efficient for a short exposure.
- At d/r0 = 3, space is < 2x more efficient.
- This technique can push the fringe-tracking limit back by ~ 3 magnitudes. It significantly improves sky coverage and utility of long-baseline arrays on the ground.
- But it does not compete with space for very-low SNR objects. Long coherent integration times are required.

Visibility calibration with Single-Mode Fiber Optics



This picture downloaded
from the FLUOR website

- Single-mode fibers are spatial filters that remove the incoherent flux and desensitize the interferometer to seeing fluctuations
- Coude du Foresto et al have demonstrated 1% calibration accuracy.
- SM fibers are used at IOTA, PTI, and are planned at CHARA

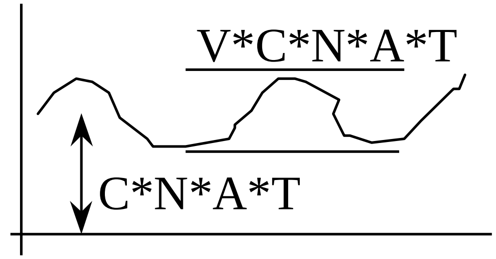
When fringe tracking is possible from the ground …

- Going to longer integration times (i.e. one long integration vs. averaging of many short frames) does not help.
- But one can improve in space by building a larger aperture.
- Then the SNR will improve linearly with the aperture diameter.
- Efficient apertures on the ground can be 1 m in diameter (0.7 microns) using moderate adaptive optics.
- Apertures in space should be larger than 1 m to have a significant advantage over ground-based interferometers.

… Space wins only if the aperture diameter is larger than is possible from the ground.

SNR for a complex object

Shot-noise limit



Object complexity = C = number of resolved cells
Surface brightness = N = photons/cell/sec
Collecting area = A = effective area/u-v point
Integration time = T
Signal from object = S = C*N*A*T

Fringe visibility = V ~ 1/sqrt(C)

This can be thought of in terms of C vectors having random phases adding together in the focal plane.

Signal to Noise ratio per UV point is

$$\mathrm{SNR} = \frac{V*S}{\mathrm{sqrt}(S)} = V*\mathrm{sqrt}(S) = \mathrm{sqrt}(NAT)$$

INTEGRATION TIME IS INDEPENDENT OF OBJECT COMPLEXITY!

Example: Object 16 mag/arcsec^2
0.01 x 0.01 arcsec (one resolution element)

SNR = 10 per u-v point requires 8000 s per u-v point

(assumes nominal throughput of 29%, static V = 0.6, bandwidth = 500 A, central wavelength = 550 nm, and two 1 m apertures.)

Increasing Object Size and Number of Baselines

- More baselines increases collecting area
  - M apertures provides M times more light
  - 0.5*M^2 more baselines
- The light available (A) per baseline goes down as 1/M
- The integration time per u-v point increases as M compared to the single-baseline case.
- Example 1:
  - 16 mag/arcsec^2, 100 resolved points over 0.1 x 0.1 arcsec
  - Integrated flux is V=21
  - 15 apertures (107 baselines), each 1 m in diameter
  - Integration time is 8000 * 15 = 120000 s (33 hrs) 10 x 10 map
- Example 2:
  - 16 mag/arcsec^2, 400 resolved points over 0.2 x 0.2 arcsec
  - Integrated flux is V=19.5
  - 30 apertures (435 baselines), each 1 m in diameter
  - Integration time is 8000 * 30 = 240000 s (67 hrs) 20 x 20 map
- Example 3:
  - same source as ex. 2, but two apertures move to 400 positions
  - Integration time is 8000 * 400 sec = a really really long time

Planet Detection by Nulling Interferometry

- The sky background is magnitude -2.1 arcsec^{-2} in the N band (10 microns)
  - This really doesn't limit things unless the optics train is cooled. Let's assume it's cooled.
- At 10 microns, the diffraction limit of the Keck aperture is 0.2 arcsec.
  - It thus sees the sky as a background of magnitude 1.4.
- An earth-like planet is ~ 15 magnitudes fainter than it's star at lambda=10 um.
- It will thus be ~ 15 stellar magnitudes below the thermal flux of the sky.
  - The problem is that the flux is "everywhere."

Planet detection in space

- In space, the prospect of seeing an earth-like planet is very challenging, to say the least.
- But a nulling interferometer can effectively suppress the central star light because that light is localized.
- It does not suppress the zodiacal light
  - But the problem is many orders of magnitude easier than from the ground.
- Ref: Gene Serabyn and C. Beichman's presentations at the summer school.

DLI: a lens-like configuration

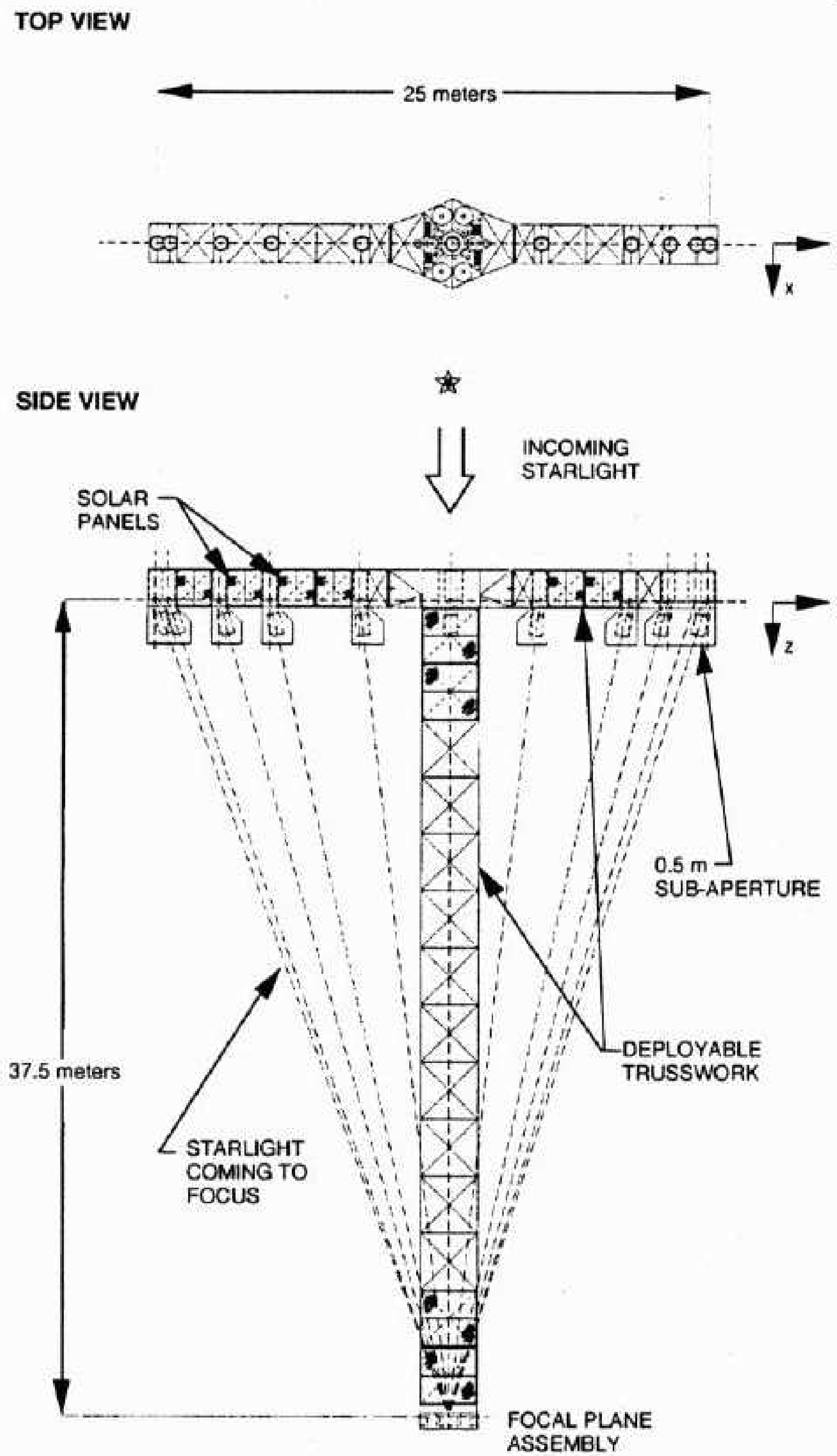


Figure 3. The Dilute Lens Imager

MUSIC:
Multiple Space-craft Interferometer Constellation

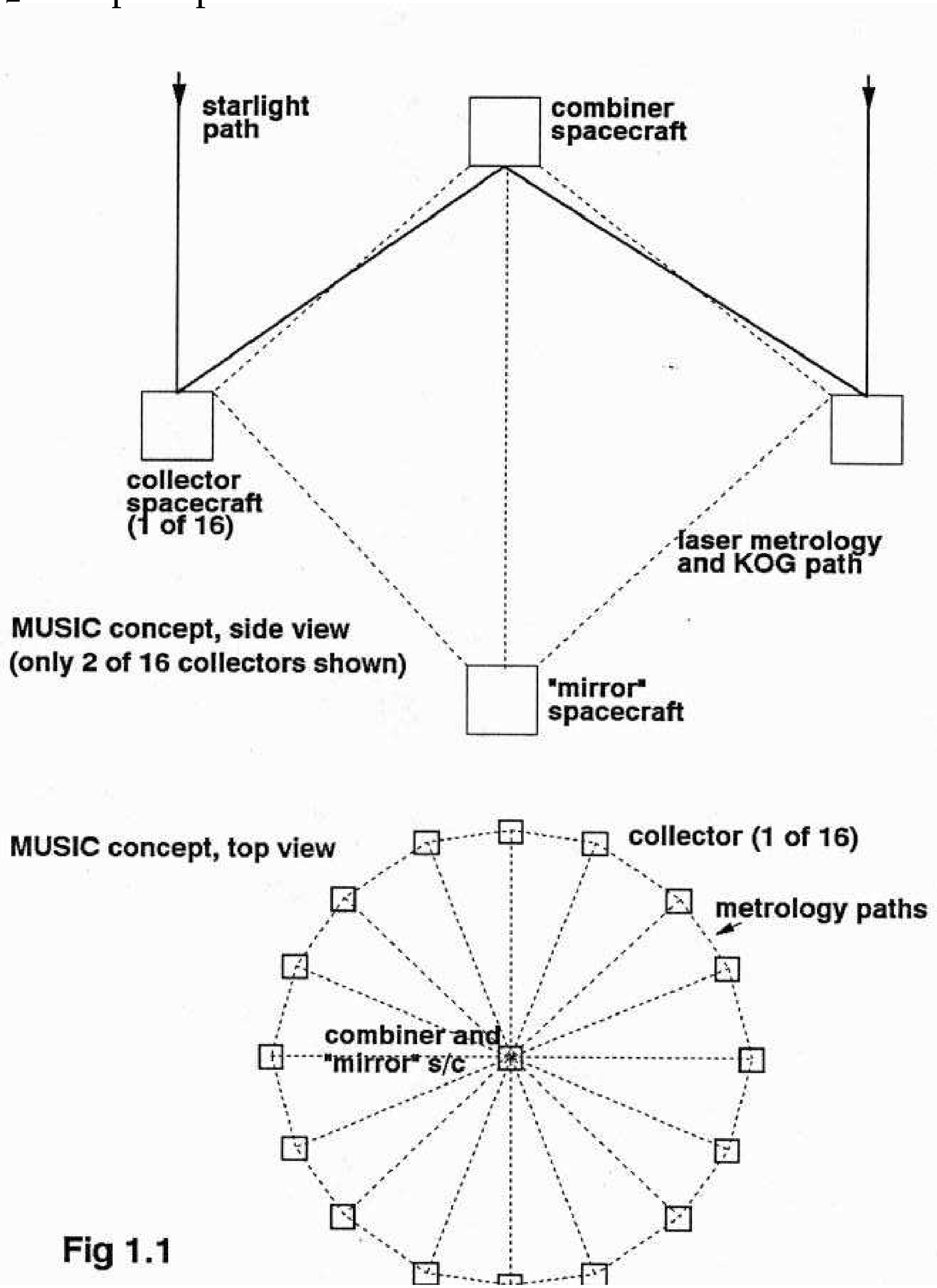
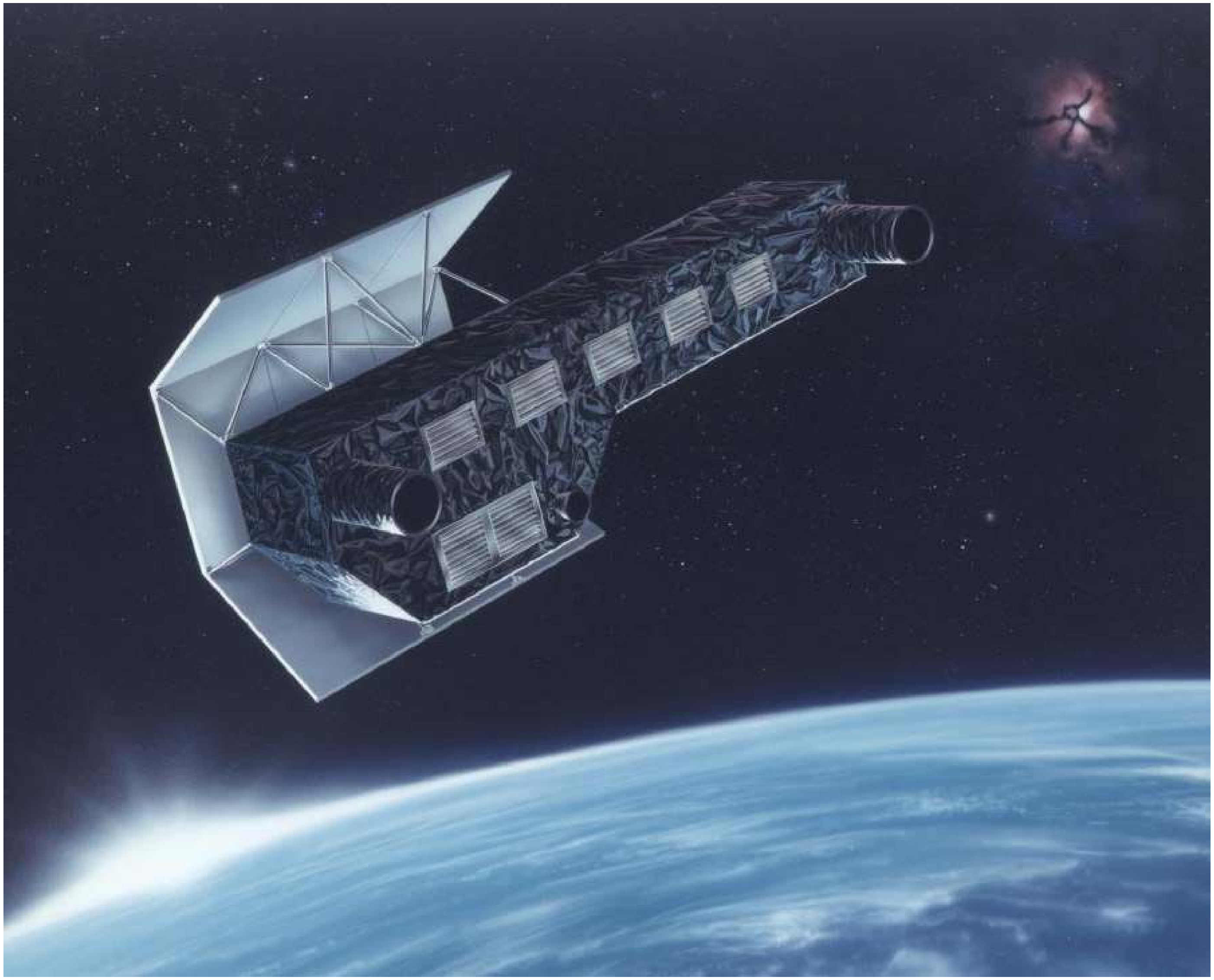
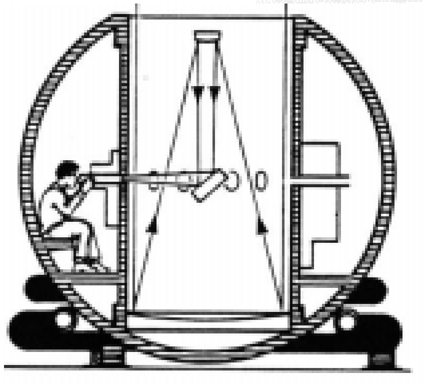


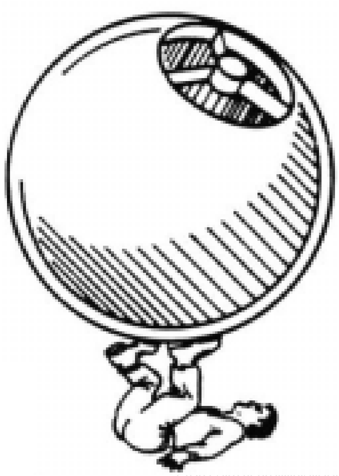
Fig 1.1

SONATA



OVLA





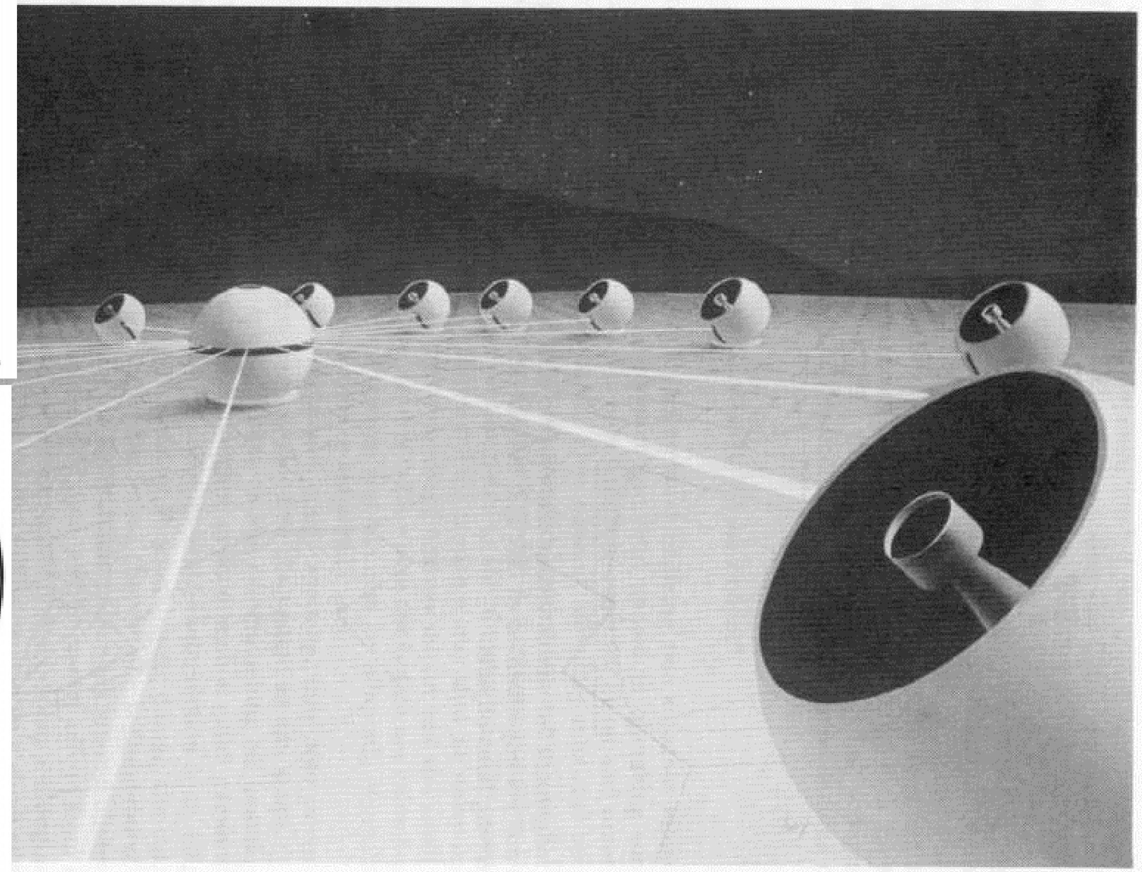
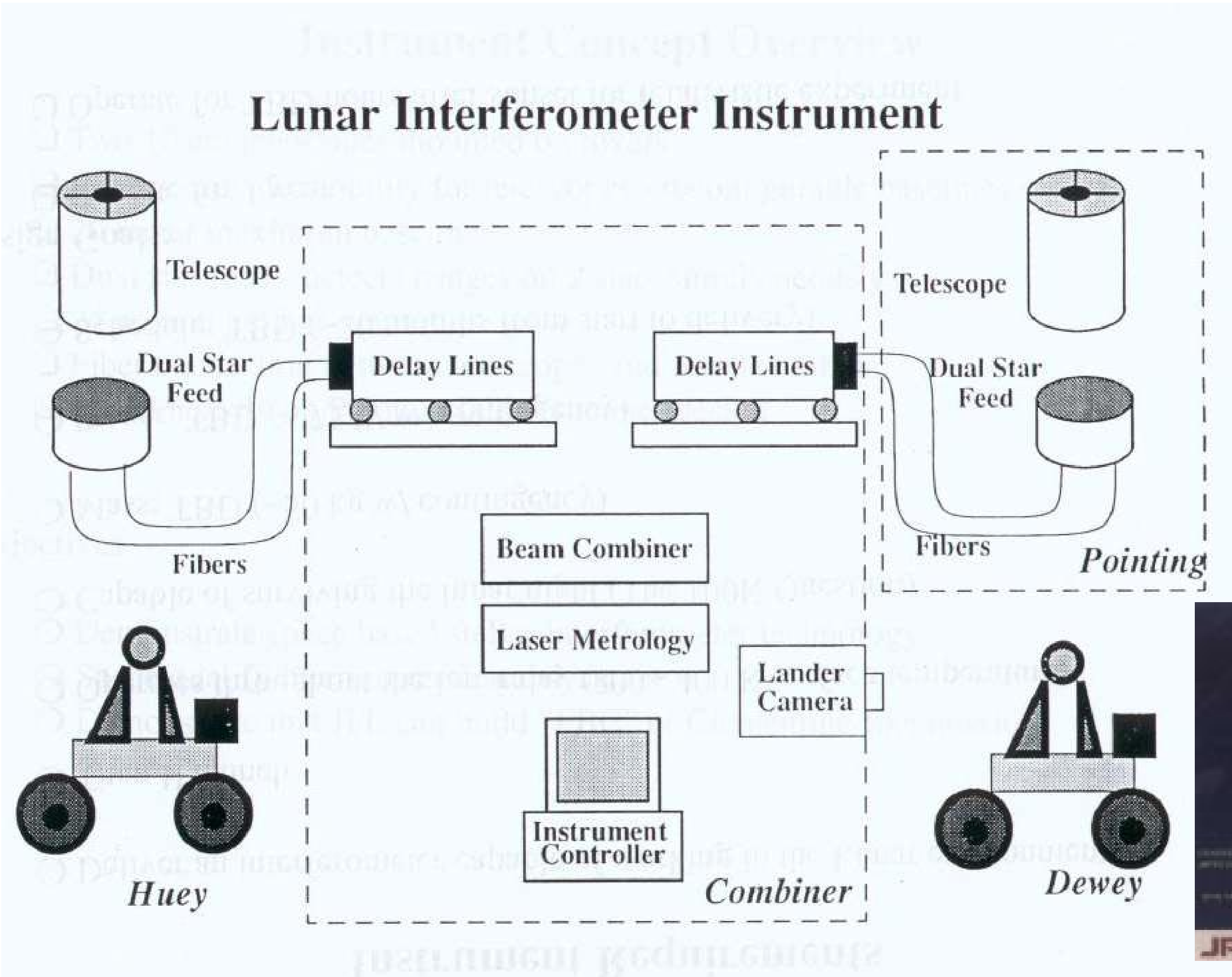
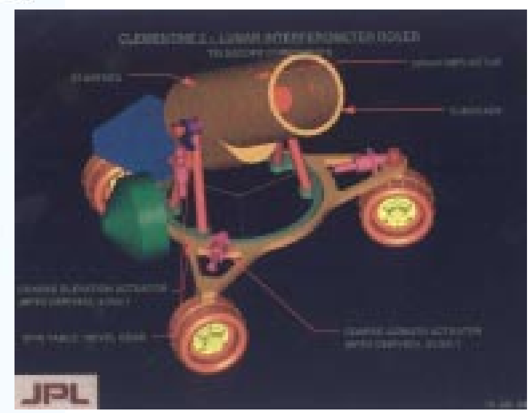


Figure 3: The Optical Very Large Array consists of many compact telescopes movable on a platform. The beams are recombined in a central station, using one of several interchangeable optical tables with different beam recombination systems. The telescopes move during the observation, so that delay lines be unnecessary. A sensitive system of laser beams keeps track of the telescope positions in three dimensions.

Clementine II Interferometer





Conclusions

- A space-borne interferometer need a phase-reference to monitor baseline motion
  - Without it, integration times will be short, and high spectral resolution will be required
- Wide angle astrometry: space is required to improve on Hipparcos. A few-micro-arcseconds may be achievable.
- Narrow angle astrometry
  - Potential on the ground to see large terrestrials.
  - No chance to detect Earths using interferometric techniques
- Imaging
  - No clear winner except for inaccessible wavelength bands
  - Large collecting apertures are required to image low-brightness complex objects.
- Nulling
  - Atmosphere severely limits effectiveness of nulling
  - Need to be above the atmosphere for planet detection
- Let's do both!!